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Published in:
Bulletin of the Geological Society of Denmark

Publication date:
2018

Document Version
Publisher's PDF, also known as Version of record

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Glad, A.C., Willumsen, M.E., Boldreel, L. O. & Clemmensen, L.B., 2018. Meandering river deposits in sediment cores, the Middle Jurassic Alma Field, Southern Danish Central Graben. © 2018 by Bulletin of the Geological Society of Denmark, Vol. 66, pp. 189–209. ISSN 2245-7070. (www.2dgf.dk/publikationer/bulletin).

Received 26 September 2017
Accepted in revised form
28 April 2018
Published online
26 September 2018

Fluvial deposits are amongst the most important terrestrial hydrocarbon reservoirs, but the complex nature of these deposits is challenging in subsurface reservoir characterisation. This study is the first detailed facies analysis of the meandering river deposits of the Middle Jurassic Alma Field situated in the southern Danish North Sea. The fluvial sandstones and their associated deposits are described and interpreted based on studies from two core sites (Alma-1X and Alma-2X). The facies analysis of the cores demonstrates the presence of three meandering river facies associations: Channel deposits, channel margin deposits and floodplain deposits. The channel deposits comprise channel thalweg and point bar sediments, the channel margin deposits include crevasse channel and crevasse splay sediments, while the floodplain deposits comprise overbank and backswamp sediments. The point bar deposits are composed of fine- to medium-grained sandstones but can contain intervals of finer grained sediments, particularly in their upper parts where they can grade into muddy sandstones or true heterolithic deposits. Preserved sand body thicknesses (channel thalweg and point bar deposits) in both Alma cores have a mean value of 2.6 m and a maximum value of 4.35 m (Alma-1X) and 6.55 m (Alma-2X). Using maximum values of channel deposit thicknesses, and assuming the preservation conditions are met, the width of the largest ancient channel belt in Alma-1X would be between 90 m and 200 m or around 900 m, depending on whether the fluvial system is mud-rich or sand-rich. The same method applied to Alma-2X gives a width of the largest channel belt between 130 m and 330 m or around 1300 m.

Fluvial sediments of the Middle Jurassic Scalby Formation (north-east England) were deposited in a sandy meandering river with sedimentary characteristics corresponding to those observed in the Alma cores. Outcrop analogue investigations of this formation were carried out to examine the architecture of the fluvial facies in a two-dimensional section with emphasis on channel thalweg and point bar deposits.

Combined evidence from core analysis and outcrop analogue studies suggests that the fluvial deposits in the Alma Field represent a mixed-load meandering river system with sandy point bars. The meandering river system developed on a coastal plain with overbank fines and organic-rich backswamp deposits. The mud-rich or heterolithic deposits in the upper part of the point bar facies intervals are noteworthy and could indicate markedly fluctuating discharge in a mixed-load river.

Keywords: Meandering river deposits, Middle Jurassic, Alma Field, core studies, facies analysis, analogue outcrop study, fluvial reservoirs.

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Meandering river deposits constitute a prominent depositional type among the non-marine environments, and their presence in various past environmental and tectonic settings makes them valuable archives of past fluvial system evolution and climatic conditions (e.g. Allen 1965, 1978; Leeder 1978; Bridge & Leeder 1979; Miall 1996, 2014). Mineral and petroleum deposits associated with fluvial environments have resulted in numerous studies of meandering river sediments and facies architecture, including analysis of depositional scales, fluvial style, and subsurface characteristics (e.g. Tyler & Finley 1991; Miall 1996, 2014; Bridge 2001). Fluvial sandstones are important, but highly heterogeneous reservoirs and account for more than 20% of the world's remaining hydrocarbon reserves (Keogh *et al.* 2007). The heterogeneity is expressed at many scales from vertical stratigraphic variations, channel body stacking, channel shape, interconnectivity and channel sediment variability (Keogh *et al.* 2007). Identification and characterization of fluvial facies in subsurface settings is challenging and highly dependent on several datasets, including core material. Facies description and interpretation of core material benefit greatly from outcrop analogue studies by illustrating the large-scale two-dimensional facies relationships (e.g. Owen *et al.* 2017).

Middle Jurassic fluvial sandstones constitute petroleum reservoirs in the Danish North Sea (Andsbjerg *et al.* 2001; Andsbjerg 2003; Schwarzer *et al.* 2007). The Alma structure is an antiform located in the southern part of the Danish Central Graben (Fig. 1); the structure was originally investigated by Maersk Oil during the early 1990s. This potential oil field of Middle Jurassic age is composed of presumed meandering river deposits with channel and channel-margin deposits of moderate to high reservoir quality (Schwarzer *et al.* 2007). The Middle Jurassic sections of Alma-1X and Alma-2X have been cored.

The purpose of this study is to present a facies analysis of the two Alma cores, with interpretations supported by an analogue study of world-class exposures of Middle Jurassic meandering river deposits of the Scalby Formation, north-east England (fig. 1; Ielpi & Ghinassi 2014).

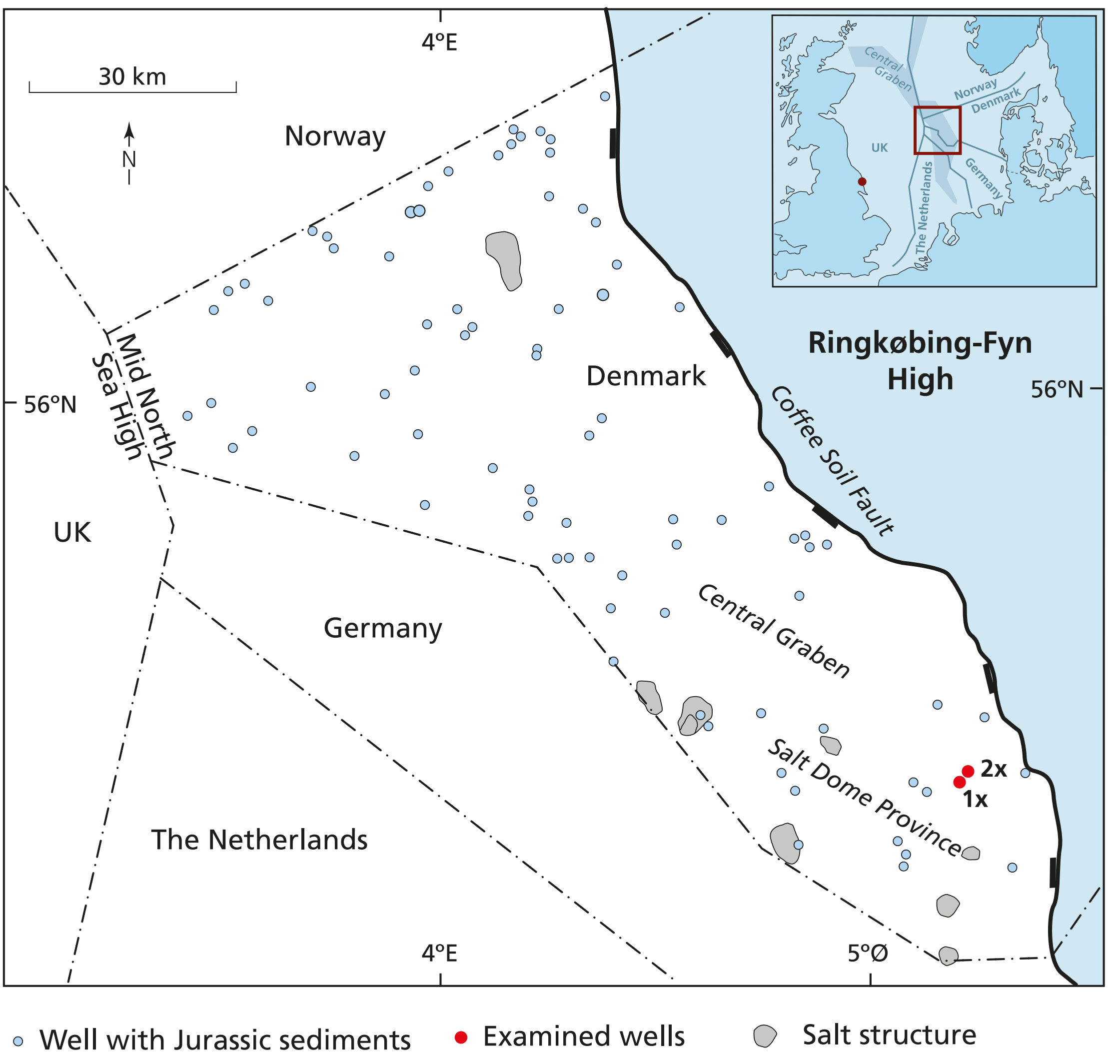

Fig. 1. Map of the Danish Central Graben with Jurassic deposits west of the Coffee Soil Fault. The studied wells of the Alma Field are situated in the south-eastern part of the Danish Central Graben and are marked by 1X and 2X with red dots. Dashed lines mark the territorial boundaries of Norway, Denmark, Germany, the Netherlands and the UK. The Scalby Formation in the eastern UK is shown by a red dot on the overview map. (Modified from Thomsen *et al.* 2013).

The Alma Field

Geological setting

The Alma Field is located in the southern part of the Danish Central Graben (Fig. 1). The Alma Field has a mapped closure of 16.8 km^2 and a relief of 300 ft (~100 m) and is situated on a faulted salt dome structure (Maersk Oil 1993a). The central part of the salt structure is severely faulted by generally N–S trending normal faults; both eastward and westward inclined faults appear to have developed antithetically (Maersk Oil 1993a; Fig. 2).

The Danish Central Graben, bounded by the Coffee Soil Fault to the east and the Mid North Sea High to the west, is part of the Central Graben which covers a large area in the central and southern North Sea (Ziegler 1990). The Danish Central Graben is made up of a series of NNW–SSE trending half-grabens and forms the southern rift arm of a failed Jurassic rift system (Møller & Rasmussen 2003). The Alma Field is situated in the Salt Dome Province, characterised by salt structures formed by Permian evaporites deposited in the North German Basin (Japsen *et al*. 2003). During the Late Triassic, regional thermal subsidence was

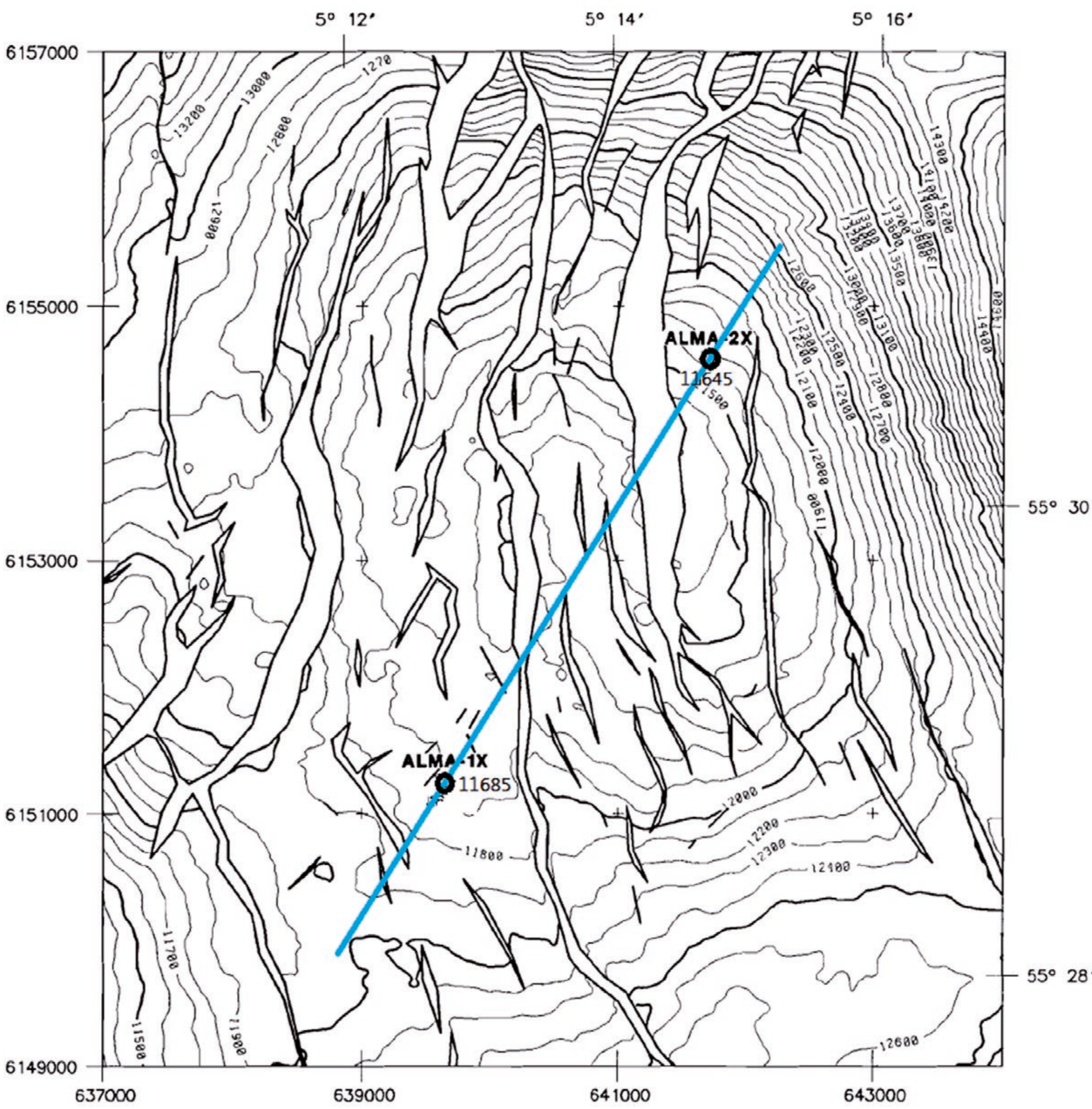

Fig. 2. Structural map of the Alma Field. The Alma Field is situated on a faulted antiform with a mapped closure of 16.8 km^2 and a relief of 300 ft (~100 m). The central part of the structure is dissected by dominantly N–S trending normal faults. The positions of the two wells are shown. The blue line is the seismic line in Fig. 4. The contour lines record the depth (in feet) of the top surface of the Lower Graben Sand Formation, equivalent to the Bryne Formation. Modified from Maersk (1993a). The length of the blue line is approximately 6 km.

initiated in the Central Graben and lasted until the beginning of the Middle Jurassic (Møller 1986). The period from the Middle Jurassic to the Early Cretaceous was characterised by an interplay of rifting, sea-level variations and halokinesis, resulting in a complex structural evolution and sediment deposition in the Central Graben (Ziegler 1990; Andsbjerg 2003; Andsbjerg & Dybkjær 2003; Michelsen *et al.* 2003). Prior to the Middle Jurassic–Early Cretaceous rifting, large areas of the North Sea Basin experienced thermal uplift resulting in the formation of the Central North Sea Rift Dome (Ziegler 1990; Japsen *et al.* 2003), which caused the Late Aalenian unconformity that influenced large parts of the North Sea including the Danish Central Graben (Andsbjerg *et al.* 2001). Following the thermal uplift, active faulting created accommodation space for deposition of Late Aalenian–Callovian sediments, which initially were continental coastal plain deposits and eventually became marine during a transgression of the Danish Central Graben in the Callovian (Andsbjerg *et al.* 2001; Husmo *et al.* 2002).

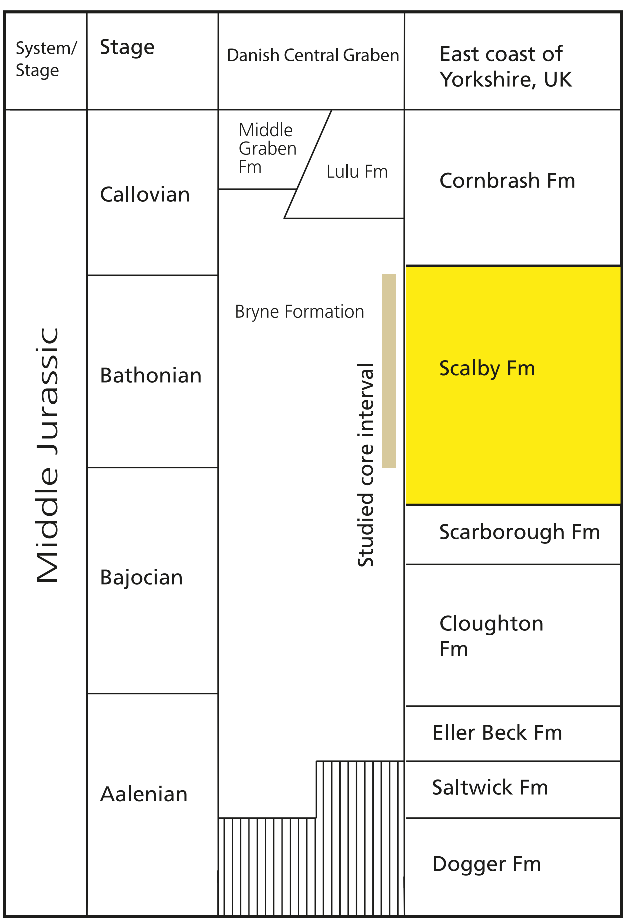

Fig. 3. Middle Jurassic stratigraphy of the Danish Central Graben (Andsbjerg 2003). For comparison, the stratigraphy of the Middle Jurassic deposits on the east coast of Yorkshire (UK) is also shown. After Ielpi & Ghinassi (2014).

Stratigraphy

The Middle Jurassic fluvial deposits of the southern Danish Central Graben were originally referred to as the Central Graben Group by Jensen *et al.* (1986) but were included in the Bryne Formation by Michelsen *et al.* (2003) and Andsbjerg (2003). The Middle Jurassic deposits unconformably overlie Triassic and Lower Jurassic deposits. Palynostratigraphic analysis of the fluvial sediments in the Alma-1X and Alma-2X cores indicates a Middle Jurassic (Bathonian) age (DGU 1991, 1993; Maersk Oil 1991a, 1993a, 1999), thus placing the sediments in the middle part of the Bryne Formation (Fig. 3). The Bryne Formation is overlain by the Callovian shallow marine Lulu Formation in the Søgne Basin and by the estuarine(?) Middle Graben Formation in the Salt Dome Province (Fig. 3). These formations are overlain by marine mudstones of the Lola Formation of Oxfordian to Kimmeridgian age (Andsbjerg 2003).

Palaeogeography

The northern part of the Danish Central Graben was characterised by an extensive coastal plain and shallow marine environments during deposition of the lower and middle part of the Bryne Formation in the Aalenian – Late Bathonian (Andsbjerg 2003). During periods of low base level, laterally migrating meandering rivers dominated sediment deposition, whereas periods of high base level resulted in distal floodplain, lake and lacustrine delta sedimentation with occasional marine influence (Andsbjerg 2003; Husmo *et al.* 2002). During deposition of the upper Bryne Formation in the late Bathonian – earliest Callovian, estuarine and tidally influenced river sediments were deposited in major incised valleys (Andsbjerg 2003). Schwartzer *et al.* (2007) showed the existence in the Danish Central Graben of meandering rivers separated by large overbank areas with coal formation during deposition of Middle Jurassic sediments (Bryne Formation?). The meandering rivers were running in southerly directions, but unfortunately Schwarzer *et al.* (2007) did not propose in which part of the Central Graben river deposition took place. Andsbjerg (2003) found that rivers in the northern part of the Central Graben were running in easterly and northerly directions.

The palaeogeography of the southern part of the Danish Central Graben is less well known, however, Michelsen *et al.* (2003) found that the lower part of the Middle Jurassic succession (Bryne Formation) is characterised by thick sandy deposits interbedded with silt- and claystones and occasional coal beds. Sedimentation took place on a coastal plain during strong fluvial influence.

Climate model experiments by Sellwood & Valdes (2006) and geological studies in the Yorkshire Basin by Morgans *et al*. (1999) indicate that the North Sea Region had a temperate, winter-wet climate during the Middle Jurassic. The presence of coal in the Middle Jurassic fluvial successions of the North Sea, including the deposits in the investigated cores, indicates mire formation under a relatively high and permanent water table (Petersen *et al.* 1998).

Data set and methodology

Internal reports and geophysical data

Maersk Oil and the Geological Survey of Denmark and Greenland (GEUS) prepared a suite of internal reports on the Alma Field that were made available for this study. The used reports are Final Well Reports Alma-1X (Maersk Oil 1991a) and Final Well Report Alma-2X (Maersk Oil 1993a), Core photos Alma-1X (Maersk Oil 1991b) and Core photos Alma-2X (Maersk Oil 1993b), Alma-1X Central Trough palynofacies (DGU 1991) and Alma-2X Central Trough palynofacies (DGU 1993) and Palynostratigraphy of the Jurassic Intervals from wells Alma-1X and Alma-2X, Danish North Sea (Maersk Oil 1999).

Maersk Oil provided a 3D seismic cube covering the Alma Field in Petrel version 2013.5. The Petrel dataset also contained petrophysical data in the form of wireline logs from the two Alma wells (Fig. 4). In this study the geophysical data is used to illustrate the structural setting of the Alma Field. Detailed interpretation of the seismic data and wireline logs are not included.

Core data

The Middle Jurassic cored intervals of Alma-1X have a core diameter of 5 cm. This core was drilled at a nearly vertical angle, with a to 1–2° offset from vertical (Fig. 4). The structural dip at the Alma-1X core site is around 1° in the same direction as the offset of the well; as a result the dip of horizontally deposited strata in the core can be neglected. The Alma-2X core sections were drilled with a diameter of 9.5 cm, and the well was oblique with a vertical offset angle of 33°–35° (Fig. 4). The structural dip at this site is around 20°, and horizontally deposited strata in the core would have a dip around 36°. This is in agreement with core observations, see later.

The Bryne Formation is represented by an interval of 117 m in the Alma-1X well (11816 to 12202 feet measured depth) and an interval of 219 m in the Alma-2X well (13657 to 14377 feet measured depth). In Alma-1X, 73.9 m (measured) of the formation was covered by

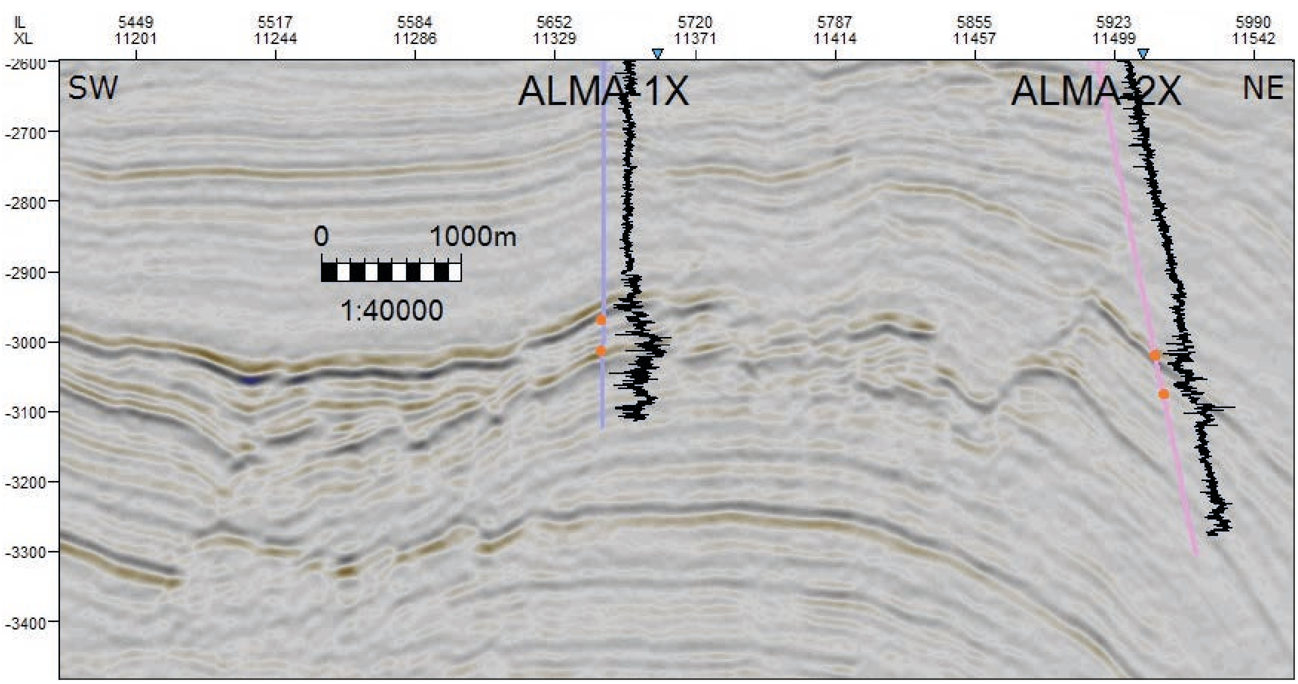

Fig. 4. Seismic overview of the two Alma wells. The studied interval in the Middle Jurassic section is delimited by the orange dots at the top and bottom of the interval. The vertical seismic resolution in the Middle Jurassic interval is calculated to be 12.5–30 m. Alma-1X is drilled vertically in an area where the Jurassic strata dip weakly SW, while the deviated Alma-2X penetrates Jurassic strata which dip relatively steeply NE. Along the wells their respective gamma ray tracks are shown. 3D seismic data set provided by Maersk Oil.

four core sections with a combined thickness of 35.4 m, and in Alma-2X 109.9 m (measured) of the formation was covered by eight core sections with a combined thickness of 60.8 m. Detailed sedimentological logs, at scale 1:10, were measured in the cored intervals of the Bryne Formation in the two wells. The narrow width of the Alma-1X core and the frequent occurrence of broken-up sections (rubble) caused some difficulties with regard to facies description and interpretation. The wider and more coherent core sections of Alma-2X made facies description and interpretation easier to carry out (Fig. 5). The logs were checked against the cores three months after the first visit to control that all details were shown correctly.

Field data

To supplement the sedimentological observations of the Alma cores and to obtain perspective on the architecture and relations of the fluvial facies elements, an analogue outcrop study was undertaken in northern Yorkshire, England. Field investigations focused on the Middle Jurassic Long Nab Member of the Scalby Formation, which is well exposed in cliff sections and contains a succession of meandering river channel, channel margin and floodplain deposits (Ielpi & Ghinassi 2014). The collected field data was used to evaluate the facies model developed for the Alma Field and to illustrate some of the challenges related to facies description and interpretation on core material. Results from the field study are briefly presented after the description of the Alma cores. However, observations from the field study are used as comparative data in the interpretation of the sedimentary facies in the Alma cores.

Fig. 5. Overview of representative core parts. Left: Alma-1X. Right: Alma-2X. The core quality of Alma-1X is considered moderate to good while the general quality of Alma-2X is considered to vary from good to very good due to the larger core diameter and more coherent cores. Alma-2X is not vertical, which results in the steep apparent dip of the strata (Fig. 4). Photographs by Maersk Oil. Scale in feet. Core parts shown are for Alma-1X: 11900’00’’–11979’04’’ (core 2), and for Alma-2X: 13830’02’’–13841’07’’ (core 2).

Facies description and interpretation

The genetic facies classification scheme used here builds on the widely used classifications by Reineck & Singh (1973) and Miall (1996) as well as on the descriptions of fluvial meandering river deposits by Ghinassi & Ielpi (2015). Three meandering river facies associations are recognised: *channel deposits* include channel thalweg and point bar facies, *channel margin deposits* include crevasse channel and crevasse splay facies, and *floodplain deposits* include overbank and backswamp facies.

The recognised facies are given as occurrence, percentage and thickness for each core (Fig. 6). The deposits, and in particular the sandstones, are tightly cemented, rarely calcareous, occasionally micromicaceous. Grains are subangular, sorting is moderate and visible porosity is poor to very poor (Maersk Oil 1991a; 1993a).

Channel deposits

Channel thalweg deposits

Description. This facies represents the most coarse-grained deposits in the two Alma cores. The sediment is composed of sand, granules and pebbles and is either a clast-rich sandstone or a conglomerate, commonly with intraformational coal and clay clasts and more rarely extraformational clasts (Fig. 7). The intraformational clasts are angular and range from a few millimetres to a few centimetres in length, while the extraformational clasts are relatively well rounded, typically of quartz, and of granule to pebble size. The channel thalweg conglomerate matrix is fine- and medium-grained sand with a light grey colour, while the intraformational clasts are dark grey and black. The sediments exhibit low-angle stratification in some cases, but are generally structureless with a random orientation of the intraformational clasts. The channel thalweg facies has an erosive and sometimes down-cutting base to the underlying sediments.

In Alma-1X the channel thalweg facies is represented by six intervals ranging between 0.05 and 0.25 m in thickness and comprises 2% of all facies. In Alma-2X the facies is represented by 16 intervals with thicknesses between 0.03 and 1.60 m (the thicker deposits are gradational into overlying point-bar deposits with numerous intraformational clasts) and constitutes 11% of all facies in this core (Fig. 6).

Interpretation. The channel thalweg deposits of the Alma cores closely resemble the intraformational conglomerate facies of Andsbjerg (2003); these sediments formed at the base of meandering river channel fills in the Bryne Formation in the northern part of the Danish Central Graben. They also share many characteristics with intraformational conglomerates seen at the base of point bar elements in the Scalby Formation (Ielpi & Ghinasi 2014 and own observations, see later). The lack of extraformational clasts in most conglomerates indicates limited supply from distant sites (hinterland), and the lithology of the intraformational clasts shows erosion of channel margin and floodplain deposits (Bridge & Jarvis 1982; Miall 1996).

Point bar deposits

Description. The lower and main parts of the sediments of this facies are primarily composed of fine- and medium-grained sandstones of brown, yellow or grey colour, but in their upper intervals the sandstones may grade into muddy sandstones or true heterolithic deposits (Figs 8, 9). The facies shows a variety of structures, including planar lamination, small-scale (ripple) cross-lamination, irregular lamination, root structures, deformation structures, microbrecciation and coal fragments or flakes. In the heterolithic intervals wavy lamination is present with some of the laminations being outlined by coal flakes. In some of the upper point bar units, mottling, iron staining

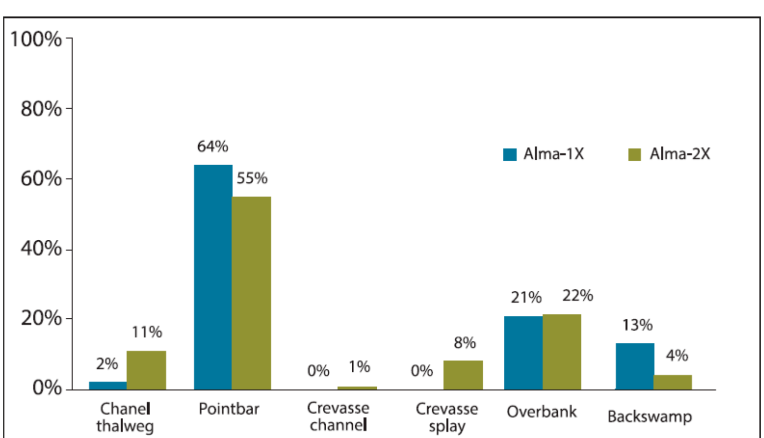

Fig. 6. Distribution in percentages of the sedimentary facies in the two sediment cores Alma-1X and Alma-2X. The percentages represent the accumulated thickness of each facies in the cored Middle Jurassic sections.

and rootlets are observed. The deposits are typically underlain by channel thalweg and overlain by floodplain deposits.

In Alma-1X such sandstones are represented by six intervals ranging in thickness from 0.4 to 3.85 m and constituting 64 % of the sediments. In Alma-2X there are 21 intervals with point bar deposits, which are 0.10–6.05 m thick and comprise 55 % of all facies. The facies forms part of channel units, which are usually initiated by channel thalweg deposits. In some cases, the sandstones are amalgamated and individual sandstone units may be as thin as 0.1 m.

Point bar strata in Alma-1X have dips between 0° and 20° with the majority around 10°–15°, while the point bar strata in Alma-2X dip between 10° and 60° with the majority around 20° and 45°.

Interpretation. The point bar deposits in the Alma cores can be compared with point bar deposits of the Scalby Formation (Ielpi & Ghinassi 2014 and own observations, see later). Point bar deposits typically display both large-scale and small-scale cross-stratification (Miall 1985, 1996, 2014). Such structures are also observed in the Scalby Formation (Ielpi & Ghinassi

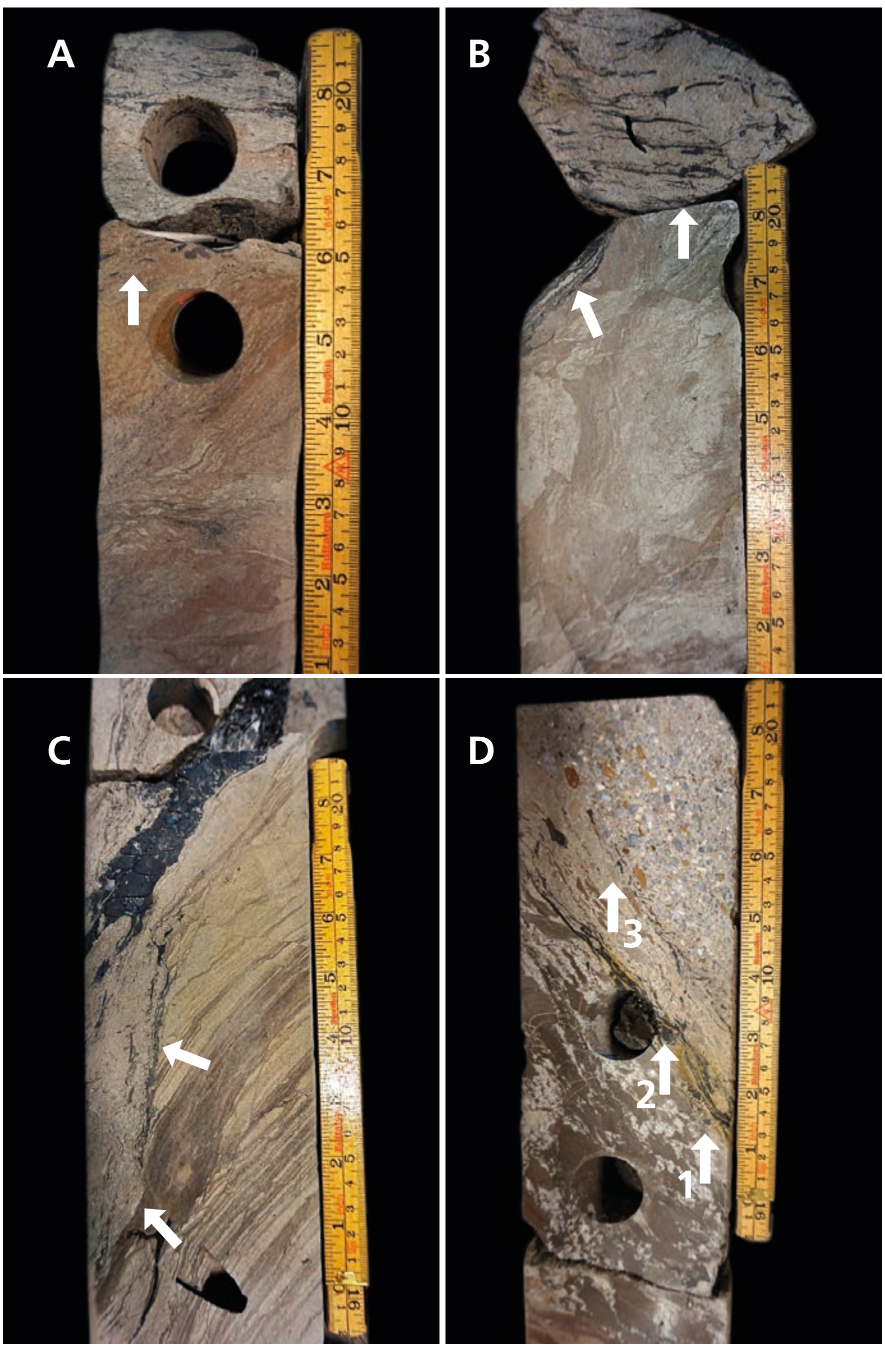

Fig. 7. Channel thalweg facies of the Alma cores. The arrows indicate the lower boundary of the channel thalweg deposit. **A**: Alma-1X, core 2/5, box 1. The channel thalweg deposit is composed of medium-grained sand with intraformational mud and coal clasts. The channel thalweg sediment overlies deformed point bar deposits with a sharp boundary. **B**: Alma-2X, core 2/9, box 15. The channel thalweg deposit is composed of medium-grained sand with intraformational coal and mud clasts. The channel base has an undulatory and sharp boundary to the underlying point bar deposits that are severely deformed. **C**: Alma-2X, core 2/9, box 2. The channel base is outlined by a down-cutting boundary to underlying point bar sands. The channel thalweg deposit is composed of medium-grained sand with small mud and coal clasts as well as one large coal clast. The point bar strata dip 40°, which is a sum of an oblique angle of the core (30–35°) and a morphological dip of the point bar of 5–10°. **D**: Alma-2X, core 7/9, box 10. The channel thalweg facies is developed as a composite deposit. An early phase of erosion (arrow 1) is overlain by medium-grained sand with extraformational clasts of granule size. Phase 2 (indicated by arrow 2) is composed of medium-grained sand with intraformational mud and coal clasts, while phase 3 (indicated by arrow 3) is composed of medium-grained sand with extraformational clasts of granule and pebble size. The composite channel thalweg deposits overlie dipping point bar strata. The ruler shows both centimetres and inches.

2014). The apparent lack of large-scale cross-bedding in the Alma point bar deposits is therefore surprising, as is the scarcity of small-scale cross-lamination. However, due to the limited dimension of the cores, large-scale cross-bedding may be hard to identify and therefore may actually be present in the Alma point bar deposits.

Fining-upward patterns occur (two examples in Alma-1X and seven in Alma-2X), as expected (Miall 1996). However, less systematic grain-size patterns are also observed and could be related to sections on upstream parts of the point bar where the flow is not fully developed (Jackson 1976). Deposits from upstream parts of the point bar elements in the Scalby Formation also display poor fining-upward trends (Ielpi & Ghinassi 2014). Some of the thinnest sandstones may represent either point bar or crevasse sediments, which are similar in lithology and structures. The sequential setting of the sandstones is used here to interpret their depositional environment. Amalgamation of the point bar deposits could indicate channel migration (or avulsion) and later reoccupation of the site by a new river course. However, observations in the Scalby Formation (see later)

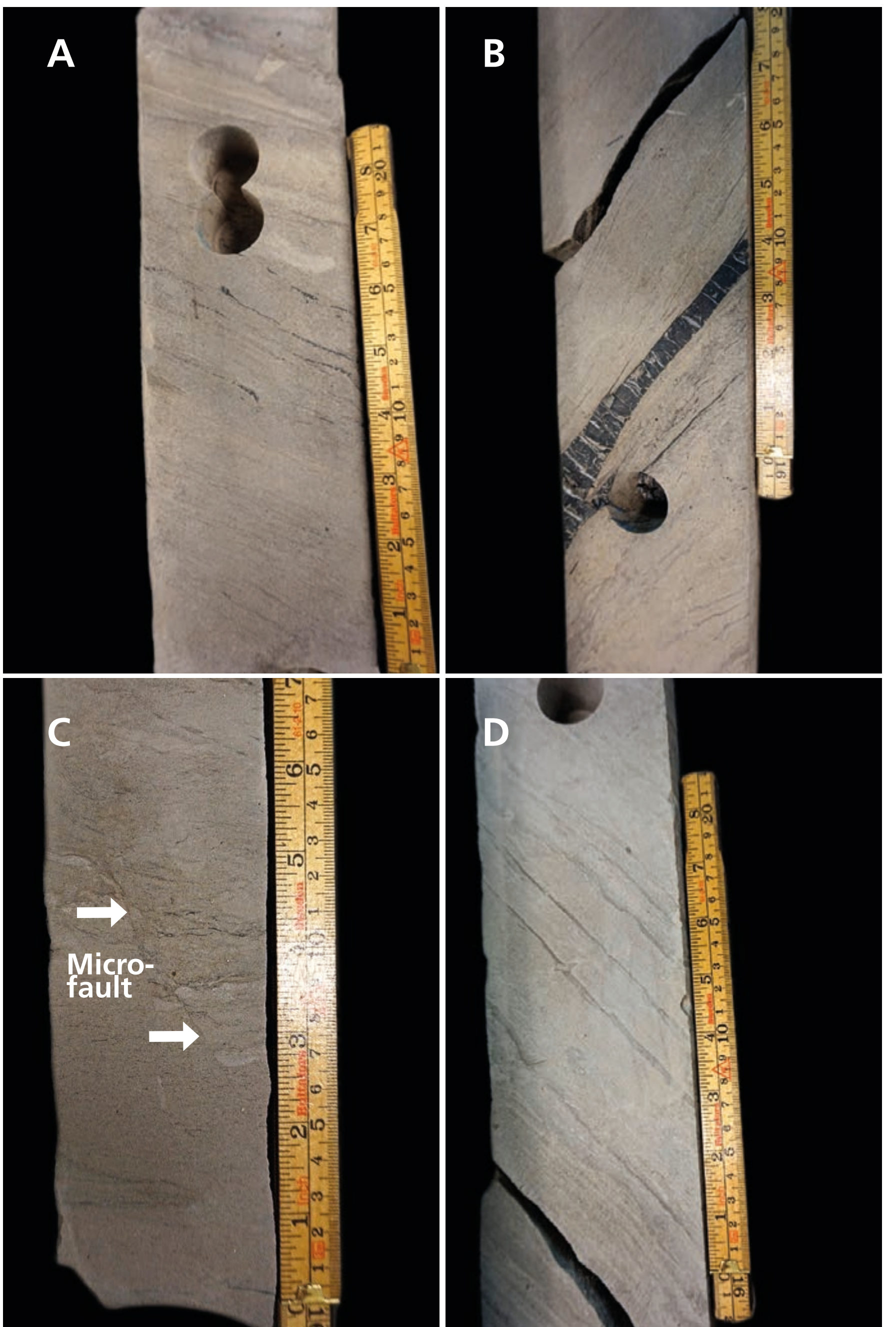

Fig. 8. Point bar facies from Alma-2X. The apparent opposite dips of the cores depend on which half of the core is seen. **A**: core 1/9, box 4. Fine-grained sand with scattered small coal flakes. The apparent dip of 15° is less than expected but could be related to a point bar surface dipping in the opposite direction of the 30–35° dip of the core. **B**: core 2/9, box 3. Fine-grained point bar sandstone with a large fragment of coalified wood. The sediment has an apparent dip of 45° which may correspond to a morphological dip of ~10°. **C**: core 6/9, box 7. Point bar deposit of fine-grained sandstone with darker streaks of silt. Microbrecciation including microfaults occur in the lower part of the core (arrows). The sediment has a low apparent dip. **D**: core 2/9, box 7. Point bar deposit of fine-grained sand with drapes of silty material. The core interval has an apparent dip of ~40°, slightly more than the dip of the core.

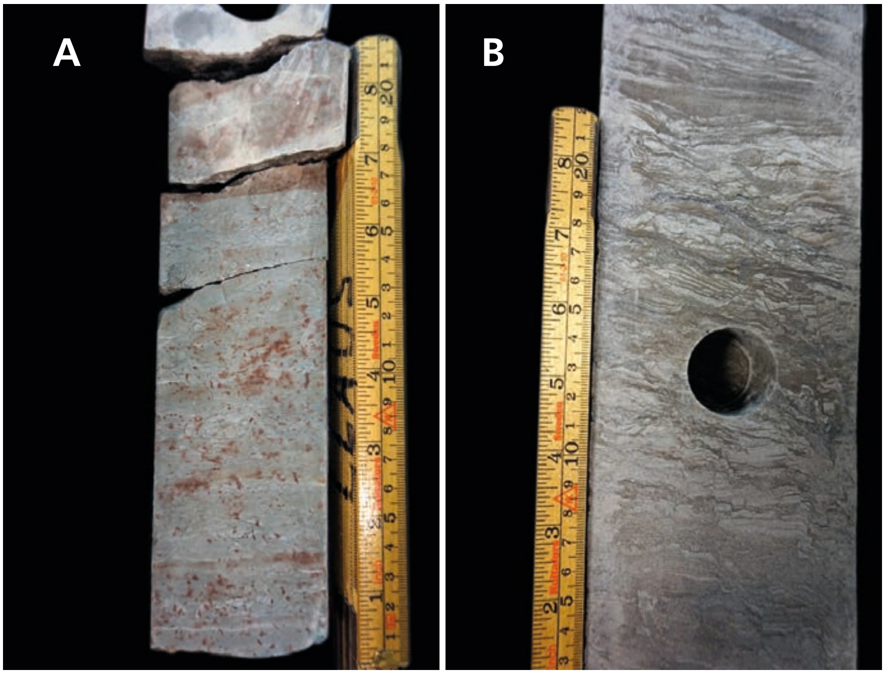

Fig. 9. Upper point bar deposits. **A**: Alma-1X, core 4/5, box 7. Upper point bar deposit composed of muddy and fine-grained sand with small dark root structures and red-brown spots of iron-enriched material. The apparent dip of the strata is 3° which is close to the morphological dip. **B**: Alma-2X, Core 6/9, box 7. Heterolithic upper point bar deposit with even and wavy lamination overprinted by mottling and microbrecciation. The measured dip of the strata is around 10°.

suggest the deposition could have taken place in only one channel during dynamic interfingering of point bar and channel thalweg deposits due to variations in flow strength and channel width with time.

Point bar sandstones in the cores (particularly Alma-2X) are not always recognised as clean sandstones but can contain various amounts of clay or silt, making them muddy sandstones, siltstones or true (inclined) heterolithic strata (Thomas *et al.* 1987). These deposits typically occur at the top of the point bar units but are also locally preserved as thin intervals in the lower or middle parts of the point bar deposits. A possible cause for the heterolithic nature of the upper point bars could be tidal influence (Pearson & Gingras 2006). However, the somewhat unsystematic nature of the heterolithic strata and the scarcity of bioturbation seem to indicate that there is another cause for the heterolithic strata. This could be fluctuating discharge of a mixed and suspension-rich river, causing alternating deposition of sand and mud on the upper point bar (Thomas *et al.*1987), or the heterolitic sediments could represent 'swale' deposits formed between scroll bars in the transition zone between the point bar and the channel margin, as observed in the Scalby Formation (Ielpi & Ghinassi 2014 and own observations, see later). However, sandy scroll bar deposits have not been identified with certainty in the Alma cores. The mud-rich to heterolithic intervals observed in some point bar deposits may also represent counter point bar deposits, i.e. sediments formed on the distal-most part of the point bar; such sediments are typically dominated by silt and can form inclined heterolithic strata (Smith *et al*. 2009). From the available core data we cannot evaluate which of the mentioned interpretations is the most likely, and therefore classify all sediments here as upper point bar deposits for the sake of simplicity.

The limited lateral extent of the cores makes it impossible to identify lateral accretion structures. In the Alma-1X core, floodplain deposits typically have dips between 0° and 5°, while presumed point bar deposits dip between 0° and 20°. In the Alma-2X core, floodplain deposits have dips between 30° and 35°, while presumed point bar deposits may dip as much as 60° or as little as 10°, although the majority of these sediment have less extreme dips centered either around 20° or around 45°. The additional dip shown by the point bar deposits probably represents a natural dip formed by deposition on a point bar slope. As we do not know how the cores were slabbed with respect to the original bedding, we cannot calculate exact dips of the Alma point bar deposits, although it seems that most had dips between 5° and 10°. In the Scalby Formation, point bar deposits typically have dips between 5° and 15° and can occasionally reach 20° (Ielpi & Ghinassi 2014 and own observations, see later).

Channel margin deposits

Crevasse channel deposits

Description. These deposits are composed of fine to-medium-grained sandstone with intraformational clay and coal clasts near the base. There is a clear erosive lower boundary and a fining-upward trend. The deposits display small-scale (ripple) cross-lamination at the base, are structureless/mottled, and show a large-scale deformation structure at the top. The facies only occurs once in Alma-2X where the deposit is 0.4 m thick and comprises 1% of all facies (Fig. 6). The channel deposit is both over- and underlain by overbank deposits.

Interpretation. Deposits similar to this facies are recognised as crevasse channel deposits in the Scalby Formation (Mjøs *et al*. 1993; Ielpi & Ghinassi 2014 and own observations, see later). Intraformational clasts, however, seem to be rare or absent at the base of the deposits, but mudstone clasts and coal fragments are common features of other Middle Jurassic crevasse deposits (Andsbjerg 2003). The crevasse channel deposits in the Alma field probably formed as the flood water broke through a levee during peak discharge. The erosive base and presence of intraformational clasts indicate relatively strong currents during deposition of the crevasse channel sediments (Miall 1996).

Crevasse splay deposits

Description. Deposits of this facies are also composed of fine- and medium grained sandstone; they are distinguished from point bar deposits and crevasse channel deposits by their lack of basal conglomerates and close association with floodplain sediments. The sediment has an irregular lamination and is frequently mottled and microbrecciated and may also contain root structures. The deposits have an even and sharp boundary to underlying sediments and a sharp to gradational upper boundary except where overlain erosively by thalweg deposits. They are typically interbedded with overbank deposits.

In Alma-2X this facies is represented by eight intervals ranging in thickness from 0.3 to 0.9 m and comprising 8% of all facies in Alma-2X; thicker units may be amalgamated. In Alma-1X there are no observed crevasse splay deposits (Fig 6).

Interpretation. These deposits of the Alma-2X core closely resemble crevasse splay deposits of the Scalby Formation (Mjøs *et al*. 1993; Ielpi & Ghinassi 2014 and own observations, see later). The crevasse splay sandstones in the Alma-2X core were probably deposited at the edge of crevasse channels as lobes and sheets under relatively high energy that could transport fine- to medium- grained sand across a mud-rich floodplain. Root structures and mottling indicate a break in sedimentation after the formation of the crevasse splay and that the surface of the sand was colonised by vegetation (Mjøs *et al*. 1993; Miall 1996; Ielpi & Ghinassi 2014).

Floodplain deposits

Overbank deposits

Description. This facies is defined to comprise all non-organic claystones, siltstones and some heterolithic deposits. The claystones are structureless and frequently show mottling, while the siltstones and heteroliths are structureless, laminated and wavy-bedded. Microbrecciation, root structures and deformation structures are common in all overbank deposits. The deposits occasionally contain millimetre-sized coal flakes. The colours are grey, yellow, brown and dark grey. Black carbonaceous mudstones are treated in the paragraph on backswamp deposits. The overbank deposits are found over- and underlying both channel margin and channel deposits.

Overbank sediments occur in five intervals in Alma-1X and 15 intervals in Alma-2X. The units are 0.1 to 2.60 m thick in Alma-1X and 0.05 to 2.70 m thick in Alma-2X. The facies constitutes 22 % of the succession in Alma-2X and 21% in Alma-1X (Fig. 6).

Interpretation. Deposits of this facies closely resemble the floodplain fines and lake fills of the Scalby Formation (Ielpi & Ghinassei 2014 and own observations, see later). The deposits also share similarities with the disturbed silty mudstones of the vegetated floodplain facies association in the Middle Jurassic Bryne Formation in the Danish North Sea (Andsbjerg 2003). The geometry of the overbank facies cannot be assessed in the sedimentary cores, and thus the facies could represent abandoned meander channels (oxbow lakes). Deposition took place during periods of overbank flooding from slowly streaming or nearly stagnant water. Mottling may indicate periods of higher biological activity.

Backswamp deposits

Description. This facies of the Alma cores comprises dark grey carbonaceous mudstones and coherent black coal beds, with a gradational transition into dark-grey overbank mudstones. The mudstone is structureless but locally contains scattered root structures and millimetre-sized coal flakes. In Alma-2X these deposits are overlain by point bar deposits and crevasse splay and channel sandstones, while they overlie point bar heteroliths, overbank sediments and point bar sandstones. The transitions are characterised by sharp and even boundaries except in one case where a crevasse channel cuts erosively down into the carbonaceous mudstone. In Alma-1X the deposits are over- and underlain by point bar sandstones and heteroliths all characterised by sharp transitions.

The backswamp deposits occur in five intervals in Alma-2X where they are 0.1 to 1.10 m thick. In Alma-1X there are two intervals 1.20 and 1.50 m thick. In Alma-1X backswamp deposits comprise a total of 13% while they constitute 4% of the total facies in Alma-2X (Fig 6).

Interpretation. This facies shows many similarities to the organic-rich floodplain fines and lake fills of the Scalby Formation (Ielpi & Ghinasi 2014 and own observations, see later), and also shares many characteristics with the organic-rich laminated mudstones of the vegetated floodplain facies association of the Middle Jurassic Bryne Formation in the Danish North Sea (Andsbjerg 2003). Backswamp sediments in the Alma cores were deposited in the floodplain area from organic and terrigeneous material. The majority of the backswamp areas probably developed as lake swamp environments with possible algae blooms, while others were increasingly vegetated and eventually became overgrown, resulting in peat/coal formation. Palynological studies of eight samples of floodplain sediments in Alma-1X revealed that they primarily formed in lake and swamp environments without marine influence. A few samples from Alma-2X contain broken/rare dinoflagellate cysts (DGU 1991, 1993). These marine dinoflagellate cysts could indicate sporadic connection to the sea or rare episodes of marine inundation during storm floods (Goslin & Clemmensen 2017).

Shoreline sandstones

Overlying the fluvial deposits (after a long non-cored section) of Alma-1X is an 8 m thick, fine- to medium-grained, light grey and yellow, structureless sandstone. This is difficult to interpret due to a complete lack of sedimentary structures; it is tentatively interpreted to represent a beach and/or shoreface environment that may record a general transgression of the area in the Callovian (Andsbjerg 2003).

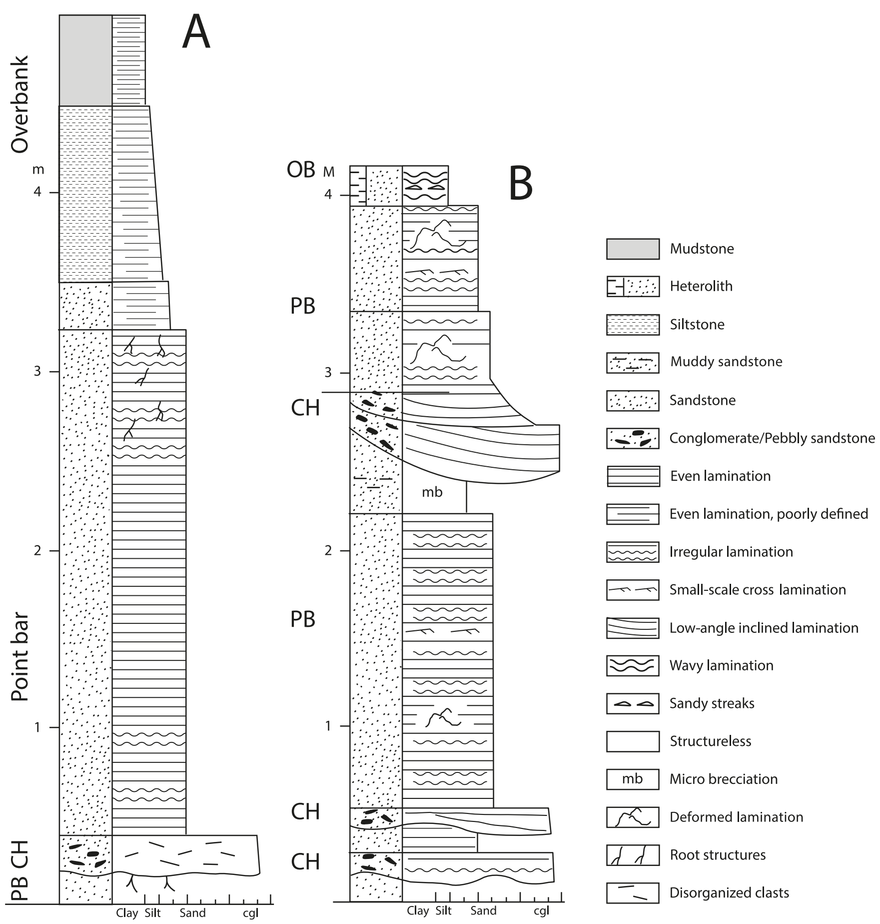

Fig. 10. **A**: Sedimentological log of a fully developed channel succession overlain by floodplain (overbank and backswamp) deposits. The contact between point bar sandstone and overbank fines is placed at the base of the siltstone. Note the dominance of even and irregular lamination in the point bar sandstones, and the apparent lack of large- and small-scale cross stratification. The apparent dip of the point bar deposits is between 0° and 10° (not shown on log). The log is based on core material from Alma-1X, core 3/5 in box 7–12. **B**: Sedimentological log of two channel successions. The lowermost channel succession (0–2.5 m) is characterised by a double channel thalweg conglomerate overlain by point bar sandstones. The repeated occurrence of channel thalweg conglomerates at the base of the succession may indicate two episodes of channel expansion separated by a period of channel contraction in line with observations from the Scalby Formation (Fig. 14). The overlying channel succession has one basal channel conglomerate overlain by point bar sandstones. Note the fining-upward pattern of both successions, the existence of ripple cross lamination in both successions, and low-angle large-scale cross bedding in the channel conglomerate of the upper succession. The apparent dip of the point bar deposits is between 30° and 40°. The log is based on core material from Alma-2X, core 2/9 in box 1–6.

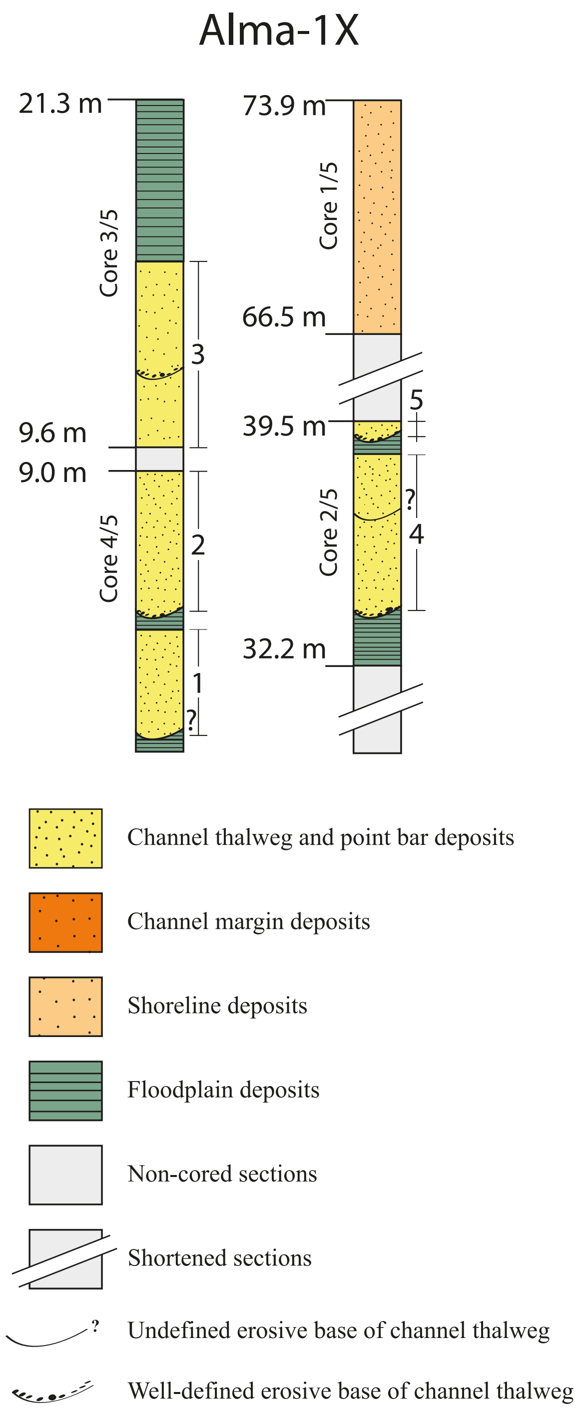

Fig. 11. Simplified sedimentological log of the investigated interval of the Alma-1X core, compiled from the original 1:10 logs. The log provides an overview of the facies with a focus on the channel deposits (channel thalweg and overlying point bar facies). Amalgamated channel deposits are grouped into sand units 1–5 which are considered to be the major reservoir units. Metres shown on the logs are measured from the base of the investigated interval upwards. Core sections are given as e.g. core 3/5. There is probably a stratigraphic break between the fluvial deposits (Bathonian) and the overlying shoreline sandstones (Upper Callovian).

Fluvial facies successions and depositional model

Channel deposits (channel thalweg and point bar sediments) form erosively bounded successions of sand-rich intervals. The channel successions are typically overlain by overbank deposits of varying thickness. Seven channel successions ranging in thickness from 0.25 to 4.35 m are recognised in Alma-1X, and fifteen individual channel successions are defined in Alma-2X ranging in thickness from 0.6 to 6.55 m. Two of the channel successions in Alma-1X and seven in Alma-2X show a well-defined fining-upward pattern (Fig. 10), while the remaining successions do not display any systematic grain-size trend. Based on the facies description and interpretation, and characteristics of the facies successions, a depositional model for the sediments in both cores is proposed.

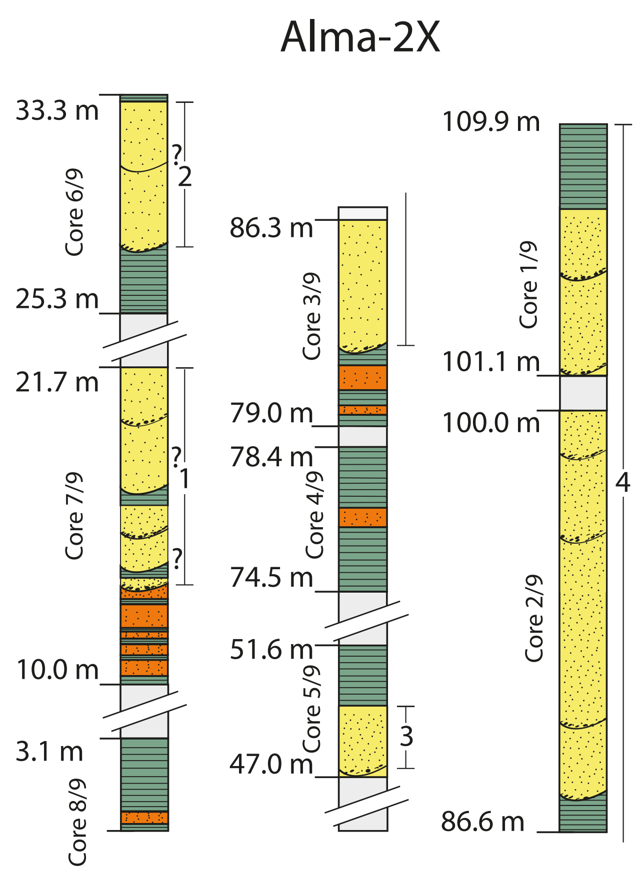

Fig. 12. Simplified sedimentological log of the investigated interval of the Alma-2X core, compiled from the original 1:10 logs. The log provides an overview of the facies with a focus on the channel deposits (channel thalweg and overlying point bar facies). Amalgamated channel deposits are grouped into sand units 1–4 which are thought to represent major reservoir units. Metres shown on the logs are measured from the base of the investigated interval upwards. Core sections are given.

The repeated presence of eroded surfaces overlain by channel thalweg, point bar, channel margin and/or floodplain deposits, in some cases observed with a fining-upward pattern, strongly suggests deposition in a meandering stream environment by autogenic processes, in agreement with the classical model for such deposits first proposed by Bernard *et al.* (1962) and Allen (1963). An alternative interpretation of deposition in a braided river system is considered less likely because of the close association with common, relatively thick floodplain facies. Compared to idealised fluvial successions from meandering streams, the observed sequences most likely formed by deposition in a sand-rich, mixed-load meandering river, corresponding to model 6 of Miall (1985). The presence of mud-rich intervals in some point bar units is intriquing but may simply indicate markedly fluctuating discharge in a mixed-load river (Thomas *et al*. 1987). The relatively frequent occurrence of floodplain and channel margin (crevasse sand) sediments suggests either relatively high rates of subsidence or frequent avulsion (Miall 1996, 2014). The balance between mud-rich floodplain deposits and more sand-rich channel deposits fluctuates over time, indicating changing avulsion rate, changing rates of subsidence, changing sediment supply or a variation of all three elements over time (Bridge & Leeder 1979).

Long-term stacking patterns

Based on the facies and facies associations recognised in the Alma-1X and Alma-2X cores, the long-term stacking pattern of the deposits is shown in Figs 11 and 12. In Alma-1X, core 4/5 is dominated by channel deposits interbedded with thin overbank units. Core 3/5 has a general fining-upward trend changing abruptly from channel deposits into floodplain deposits. Core 2/5 shows a coarsening-upward trend from floodplain into dominantly channel deposits. Finally, core 1/5 is exclusively composed of presumed shoreline deposits that were only briefly considered for this study.

In Alma-2X, core 8/9 has one thin channel margin unit at the base and is otherwise composed of floodplain sediments. Core 7/9 shows a transition from floodplain and channel margin deposits into channel deposits with subordinate floodplain interbeds. Core 6/9 shows a well-developed coarsening-upward trend from floodplain into channel deposits. Core 5/9 illustrates a change from channel to floodplain deposits. Core 4/9 is composed of floodplain deposits with a single channel margin unit. Core 3/9 has a coarsening-upward pattern with floodplain and channel margin deposits at the base, overlain by channel deposits. Core 2/9 is an alternation between floodplain and channel deposits. Finally, core 1/9 is composed of interbedded channel sands and floodplain deposits with a single channel margin unit.

Due to the near-amalgamated nature of some of the channel successions, they have been divided into five channel groups (sand units) in Alma-1X and four channel groups (sand units) in Alma-2X (Figs 11, 12). This division has been made in order to define suitable reservoir units.

The Scalby Formation: an analogue outcrop study

The Middle Jurassic (Bathonian) Scalby Formation is situated in the Cleveland Basin, North Yorkshire. The Scalby Formation is a fining-upward succession that unconformably overlies the marine Scarborough Formation and can be subdivided into the lower Moor Grit Member of fluvial (meandering river) channel and point bar sandstones and the upper Long Nab Member of floodplain–paralic mudrocks and subordinate fluvial sandstones. The untilted fluvial deposits occur along an outcrop belt (vertical coastal cliffs and horizontal tidal platforms) for approximately 4 km which makes the study of the ancient point-bar deposits and the overall fluvial geomorphological architecture particularly favourable (Ghinassi & Ielpi 2015).

The facies classification developed for the Alma cores is also used to describe the meandering river deposits observed in the Long Nab Member of the Scalby Formation. The Long Nab Member comprises the same three facies associations as the Alma cores: *channel deposits* including channel thalweg and point bar facies, and in addition chute bar, scroll bar and oxbow lake facies; *channel margin depo*sits including crevasse channel, crevasse splay and levee facies; and *floodplain deposits* including overbank and backswamp facies.

As point bar and associated chanel thalweg deposits are considered the most characteristic facies of ancient meandering river deposits (Miall 1985, 1996, 2014), we only describe these two facies from the Scalby Formation. Additional facies comprising channel margin and floodplain deposits are described briefly. We investigated primarily the cliff exposures of the Long Nab Member, while Ielpi & Ghinassi (2014) made most of their observations in the tidal platform exposures of the Mor Grit Member.

Channel thalweg deposits

This facies is typically an intraformational conglomerate or a sandstone with scattered intraformational clasts including mud and coal fragments of overbank and backswamp origin. The conglomerates show all transitions between clast-supported and matrix-supported deposits. The clasts are angular to subrounded, lie in a fine- medium-grained sandstone matrix and have typical sizes between 0.01 and 0.05 m, but can be up to 0.1 m. The clasts are disorganised and display no size sorting. The contact to underlying sediments can be relatively sharp with an irregular outline. Observed from a distance the facies forms the base of the fluvial sandstone bodies. The thalweg facies deposits are typically overlain by point bar sandstones with accretion strata dipping at low angles. Laterally, channel thalweg deposits show intricate contacts with point bar sandstone varying from small-scale stepwise contacts to large-scale interfingering (see later). The deposits are 0.1 to 2.40 m thick, most frequently between 0.2 and 1 m.

Point bar deposits

The point bar deposits are composed of fine-grained or medium-grained sandstones with low-angle dipping lateral accretion surfaces; internally the sandstones show even lamination, small-scale cross lamination sometimes developed into climbing ripples, and less common large-scale cross-bedding. The point bar deposits may show fining-upward trends or be without clear change in grain size. The lateral accretion surfaces that define the point bar unit deposits have in most examples a dip of 5–15°. Measured point bar successions are between 0.3 and 3 m thick and typically have sharp and erosive or interfingering contacts with channel conglomerate at the base (see later). They are typically overlain by (or interfinger with) mud-rich floodplain deposits (see later).

Ielpi & Ghinassi (2014) found that point bar deposits comprise up to 45% of their planform exposures. They are formed of inclined bedsets with typical dips between 5° and 15° and occasionally reaching 20°. In vertical sections they appear as fining-upward sandstone units overlying a basal intraformational conglomerate. The sandstones are fine- to coarse-grained with scattered mud clasts or coal fragments; they are dominated in their central parts by interbedded ripple cross-laminated and wavy plane-parallel-laminated sediments associated with massive mudstones. Point bar top deposits are enriched in iron oxide and siderite (Ielpi & Ghinassi 2014).

Crevasse channel deposits

Crevasse channel deposits are composed of fine- to medium-grained sandstone with erosive bases, and there is an apparent lack of a basal conglomerate. The sandstone is structureless to evenly laminated. Observed from a distance the deposits possess an extensive sheet-like geometry with pinch and swell geometry. They are interbedded with floodplain deposits and are typically between 0.3 and 0.5 m thick; the thicker and truly channel-shaped parts of these sandstone bodies are around 5–10 m wide.

Crevasse splay deposits

Crevasse splay deposits are composed of fine-grained sandstone that is structureless or evenly laminated. The deposits have thicknesses between 0.1 and 0.3 m and are traceable for over 100 m; viewed from a distance they form sheet-like sandstone bodies. They are over- and underlain by dark grey floodplain deposits; their contacts to the underlying sediments are typically sharp.

Overbank deposits

These deposits are composed of siltstone, silty claystone and claystone with a varying amount of organic material and thereby colours from pale to dark grey. The mudrocks are 0.3 to 3 m thick and may stretch laterally for several hundreds of metres. Viewed from a distance they have a sheet-like geometry and alternate with the crevasse splay and crevasse channel sandstones. The overbank deposits are generally structureless but may exhibit signs of mottling and pedogenic overprints. There is a gradational transition from the overbank to the backswamp facies.

Backswamp deposits

The backswamp deposits include all organic-rich claystones and siltstones as well as carbonaceous mud and coalified wood. The high content of organic material gives the fine sediment particles of this facies a dark grey to black colour. *In situ* deposits of coal are not recognised in this facies although coal fragments, including large tree stumps, occur within other facies. The backswamp sediments are 0.05 to 0.5 m thick and may extend laterally for several hundreds of metres. The backswamp sediments are generally structureless but have some indication of pedogenic overprinting and mottling.

Facies geometry

The geometries of the channel thalweg and point bar facies (channel deposits) of The Long Nab Member are illustrated in some detail at two sites. At the first site the channel deposits form a 4–6 m thick sand sheet which can be traced laterally for at least 85 m. The central part of the sand sheet is cut by a lens-shaped unit composed of basal thalweg conglomerates overlain by point bar sandstones with lateral accretion surfaces (Fig. 13). Thus, the sand sheet is an amalgamated deposit formed by two or more episodes of channel construction (and migration) within the ancient meandering river channel belt. The lens-shaped sand unit records the final phase of meandering river deposition at this site.

Another site demonstrates that one side of a channel system is well exposed, while the other side is poorly defined. The exposed side of the channel body is clearly lens-shaped and the channel fill displays an intricate interfingering of point bar sandstones and channel thalweg conglomerates (Fig. 14). The width of these interfingering channel deposits is around 15 m, and the deposits have a cumulative thickness of more than 3 m. This sedimentary architecture would probably indicate alternating periods of expansion and contraction of the channnel thalweg induced by discharge variations.

Some of the exposed channel deposits in the Scalby Formation grade laterally and upwards into floodplain deposits, and one mud-rich tongue is seen to split individual point bar sandstones (Fig. 14A). Such an architecture could explain the unexpected occurrence of some fine-grained intervals in the lower and middle part of some Alma point bar deposits.

Fig. 13. **A**: Overview and **B**: close-up of a channel unit in the Scalby Formation. The channel deposits form a sheet-like body of sandstone containing in its central part (with the person) a clear channel-shaped body. This locality thereby demonstrates the different size and morphology of a channel body and a channel belt body. Darker coloured floodplain deposits overlie the channel deposits. Note the gently dipping lateral accretion surfaces in the central channel body indicating channel and point bar migration to the north, and the cut bank just to the right of the person.

Discussion

Facies characterisation

Facies description and recognition in sedimentary cores is limited by core width and quality, and field investigations of the architecture and contacts of the fluvial facies of the Scalby Formation were important for the interpretation of the sedimentary cores. Particularly the observation of the interfingering nature of channel thalweg conglomerates and point bar sandstones is valuable, as it illustrates a vertical repetition of these two facies (Fig. 14B). Thus, the occurrence of channel thalweg deposits only separated by thin point bar deposits as illustrated in Fig. 10 could reflect deposition within the same channel system and thereby not represent erosion by a later channel system. The observed pattern is therefore interpreted to be caused by a dynamic interfingering of point bar and channel thalweg deposits due to variations in flow strength and channel width.

Channel and channel belt dimensions

Lateral migration of meandering rivers over time create channel belts (Fig. 15; Milliken *et al*. 2012). A major concern in the reconstruction of fluvial architecture in the subsurface is the size and width of the channel fill, as well as that of the channel belt sandstones. Gibling (2006) studied scaling relationships in ancient fluvial deposits, but more precise data on these relationships can be obtained from modern fluvial systems. Milliken *et al*. (2012) found statistical relationships between channel thickness, channel width and channel belt width in modern systems (Fig. 15). They divided meandering river systems into Low-Net End Members (mud-rich systems with highly aggradational stacking) and High-Net End Members (sand-rich systems with low aggradational stacking). These studies found that in the Low-Net End Member systems the channel belts are 20–50 times wider than the channel sandstone thickness, while in the High-Net End Member systems the channel belts are about

Fig. 14. Cross-section of meandering river deposits in the Scalby Formation. **A**: The western margin of the exposure shows light yellow point bar deposits that interfinger laterally with dark grey overbank mudstones (only partly seen on the photo). The whole succession is overlain by dark grey overbank mudstone. This section illustrates the presence of tongues of fine-grained material between sandstone lenses of upper point and scroll bar origin. **B**: The central part of the exposure with eastward-dipping point bar sandstones interfingering with channel thalweg conglomerates. Vertical length of ruler *c*. 1 m.

200 times wider than the thickness of the individual channel deposits. This relation requires preservation of the complete succession.

Channel thalweg and point bar successions (channel deposits) in the Alma-1X core have a mean thickness of 2.60 m with a minimum thickness of 0.25 m, and a maximum thickness of 4.35 m. In Alma-2X the corresponding values are a mean thickness of 2.60 m, a minimum thickness of 0.6 m and a maximum thickness of 6.55 m. Using maximum values of channel thicknesses and assuming the preservation conditions are met, the width of the largest ancient channel belt in Alma-1X would be between 90 and 200 m (Low-Net End Member) or around 900 m (High-Net End Member). In Alma-2X the width of the largest channel belt would be between 130 and 330 m (Low-Net End Member) of around 1300 m (High-Net End Member). The predicted channel belt dimensions in the Alma

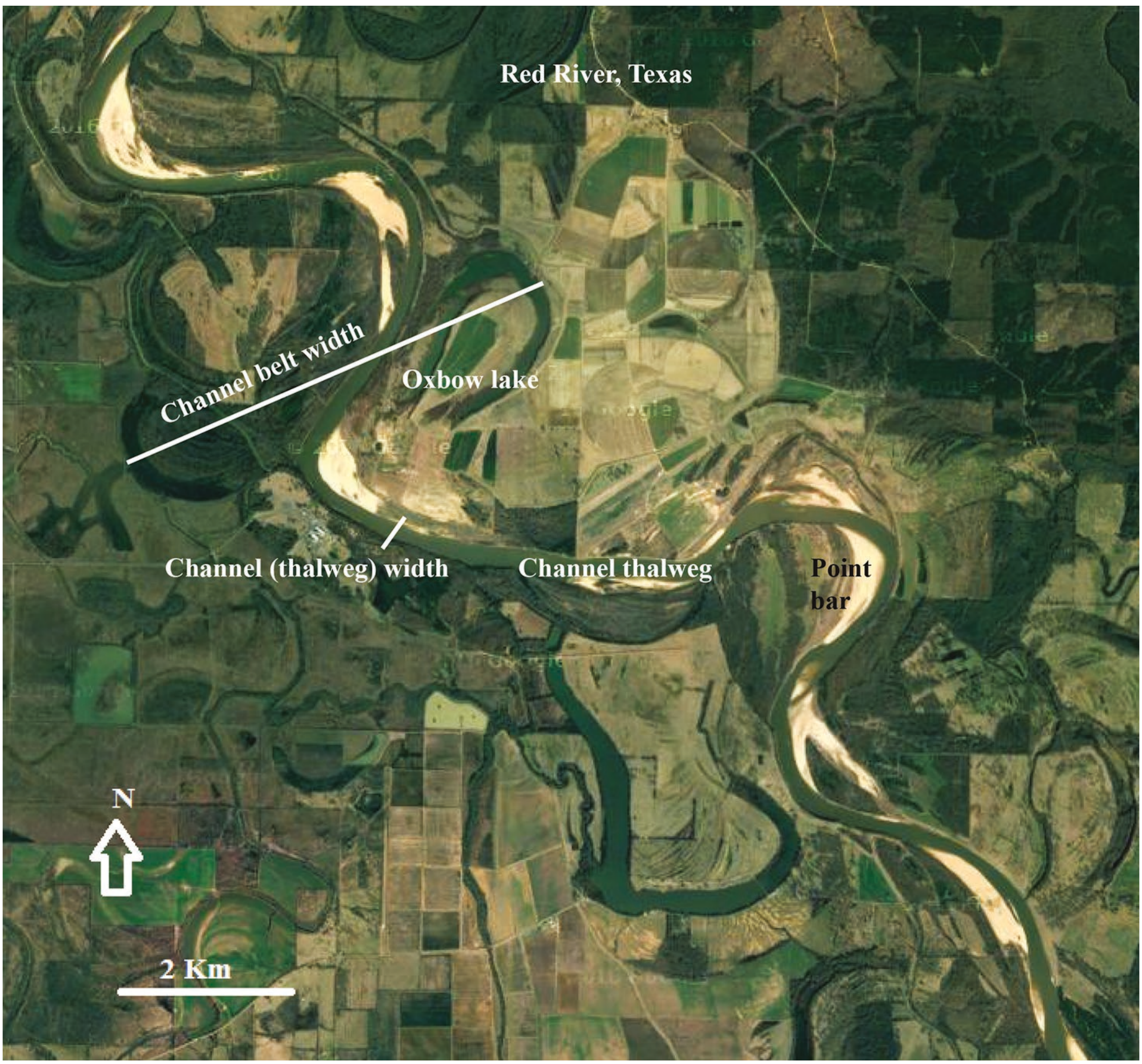

Fig. 15. Satellite image of the Red River, Texas. The photo illustrates two of the channel environments and related facies recognised in the Alma cores: channel thalweg and point bar deposits. The sandy point bars flank the meandering channel (thalweg). The distance between the outermost abandoned or active bends of the most recent river system defines the channel belt width, which is considerably larger than the width of the channel (the thalweg). The channel belt width of the Red River is of the same order as the channel belt width of the rivers in the Alma cores. The Red River in this image is situated inland, while the rivers in the Alma cores probably were situated close to the coast, with wide overbank areas in which mud was deposited and coal formation was favoured. Photo from Google Maps.

fluvial system would characterise these fluvial-channel bodies as medium in the Low-Net End Member scenario but as wide in the High-Net End Member case (Gibling 2006). The preservation of floodplain fines in the present study would indicate that at least parts of the Alma systems were formed in the Low-Net End Member scenario. According to Milliken *et al*. (2012) such systems are typical in meandering river systems close to the coast, dominated by avulsion processes.

Coastal vs. inland setting

The lack of any marine indicators in Alma-1X suggests that the fluvial system developed here was situated somewhat inland and possibly formed part of a wide coastal plain. The presence of very rare dinoflagellate cysts in Alma-2X (particularly near the top of the studied interval) suggests fluvial deposition in a coastal setting with possible rare marine inundations during storm events (Goslin & Clemmensen 2017). The formation and preservation of heterolithic and mud-rich uppermost point bar as well as common floodplain deposits, including coals from backswamps in both cores, would be in line with a coastal setting with subsidence and a high preservation potential.

Autogenic vs allogenic control

The stacking pattern of facies in the two Alma cores can be used to extract information on the avulsion rate of the fluvial system (autogenic control) or changes in base level (allogenic control). Base level is controlled by either subsidence or rising sea level (Miall 2014). Fine-grained floodplain sediments are the dominant sediments deposited (and preserved) during periods of rising sea level, while channel and channel margin sands constitutes the dominant sediments deposited and preserved during stable or slowly rising base level (Miall 2014). Another factor controlling the architecture of the fluvial system is avulsion. Avulsion is the process by which a meandering river shifts its primary course abruptly, and frequent avulsion leaves less time for lateral migration of the river, causing the formation of narrow channel sands (Miall 2014). Milliken *et al*. (2012) also state that narrow channel sandstones (ribbon sandstones) form in a Low-Net End Member system dominated by avulsion processes.

This study found that floodplain deposits comprise about 34% of the core material in Alma-1X and about 26% in in Alma-2X (Figs 11, 12). This is interpreted to reflect an overall high preservation rate due to a rising sea level on a coastal plain with relatively frequent avulsion. However, several intervals in the cores contain amalgamated channel sandstones (channel unit 3 and 4 in Alma-1X, and channel unit 2 and the main part of channel unit 4 in Alma-2X). These intervals may therefore represent times with a slowly rising or stagnant sea level or, perhaps more likely, periods of less frequent avulsion. These intervals may therefore also be characterised by the widest channel belt sandstones.

Conclusions

Studies of sedimentary cores of the Middle Jurassic Alma Field indicate that deposition took place in mixed-load meandering river systems. Channel successions are typically initiated by channel thalweg conglomerates overlain by point bar sandstones. The point bar sand cores are relatively well sorted with most sand being fine- to medium-grained. In some channel successions the point bar units show a fining-upward of grain size and many units are overlain by mud-rich floodbasin deposits. The occurrence of muddy and heterolithic upper point bar deposits is striking and suggest a high preservation potential of the point bar sediments and markedly fluctuating discharge in a mixed-load river.

The stacking pattern of the fluvial facies suggests that the fluvial system switched from a mud-rich Low-Net End Member system with high aggradational rates and frequent avulsion to a sand-rich High-Net End Member system with low aggradational rates and less frequent avulsion. The width of the largest ancient channel belt in Alma-1X would be between 90 and 200 m (Low-Net End Member) or around 900 m (High-Net End Member). In Alma-2X the width of the largest channel belt would be between 130 and 330 m (Low-Net End Member) of around 1300 m (High-Net End Member). The predicted channel belt dimensions in the Alma fluvial system would characterise these fluvial-channel bodies as medium in the Low-Net End Member scenario but as wide in the High-Net End Member case.

The study of the Scalby Formation broadly supports the mixed-load meandering river model proposed from the core studies and adds significantly to the understanding of scaling, geometry and internal contacts between the facies. In particular, the channel thalweg and point bar deposits often have a repetitive interfingering contact, and thus the channel thicknesses in the core studies could be misinterpreted and thought to represent numerous minor channel events rather than one. The observations revealed marked lateral variations across the cliff profiles. The geometrical outline of the facies elements, such as channel deposits, show changes in thickness and shape, and thus the facies given in a well could be very different some tens of metres away. On a larger scale (hundreds to thousands of metres), the Long Nab Member in the Scalby Formation illustrates that the channel sand bodies occur sporadically and are separated by wide intervals of channel margin and floodplain deposits.

These observations indicate that there are some difficulties related to defining subsurface channel sand bodies from single wells. Such a well may be located in an interchannel area and thereby yield an underrepresentation of channel sandstones; if it is located in an area with a concentration of fluvial channel sandstones there is a risk of overestimating the amount of such sandstones.

Acknowledgements

This research has received funding from the University of Copenhagen and from the Geological Society of Denmark (DGF). We are thankful to the cientific editor Henrik Tirsgaard and the reviewers Henrik Olsen and Gunver Krarup Pedersen who provided detailed and constructive reviews. Lotte Melchior Larsen is thanked for her thorough and constructive corrections to the manuscript. The Danish Underground Consortium (DUC) is thanked for granting permission to publish the paper, Maersk Oil is thanked for assisting with acquiring data and core studying facilities, and Schlumberger is thanked for issuing a University grant to University of Copenhagen (Petrel).

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